Thick, Large Area Silicon Detectors for a Future X-ray Timing Mission

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Abstract.
We report on progress in developing thick silicon detectors for X-ray and gamma-ray astronomy. Silicon detectors offer good spectroscopy at reasonably low cost and with low internal background in the energy range between 5-50 keV. This technology offers a smooth energy response and a very fast timing response for high rate applications. We are testing large area, double-sided 2mm thick detectors for applications requiring large quantities of silicon. Our current laboratory prototypes are 63 x 63 mm in area, and we will soon have detectors that are 95x95 mm in area and with thicknesses up to 3 mm. As part of our prototyping efforts, we are developing double-sided strip detectors, pixel detectors, as well as hybrid pixel/strip detectors. We present our latest laboratory results in terms of imaging and spectroscopy, as well as our progress in developing and integrating custom readout ASICs. These detectors and electronics, while not a perfect match for a next generation X-ray timing mission, form a good basis for the design of dedicated large area detectors in the 5-50 keV energy range.

INTRODUCTION

In recent years there has been a growing interest in planning for a new X-ray timing mission to build on the successes of the RXTE mission [1], and most notably the low energy PCA (Proportional Counter Array) instrument. To obtain a significant increase in sensitivity over RXTE, a baseline of 10 times the active area of the PCA instrument has been suggested [2], or roughly 10 square meters of instrumented area. If the technology of PCA were to be used, the construction effort would be ten times larger, because the gas detectors were largely hand-crafted. It is therefore worth exploring alternative technologies. Silicon detectors are an attractive alternative because, like most silicon devices, they are relatively straightforward to mass produce once they have been designed. Small silicon detectors are being used successfully for high resolution X-ray spectroscopy and have even been used on the Mars rover. To cover the energy range of interest, the detectors need to be much thicker than those that are normally used. Increasing the thickness is a challenge because the depletion voltage required to operate a detector typically increases as the square of the thickness of the detector. Progress has recently been made [3] in developing such detectors by combining much improved raw material with detector designs that use many guard rings to control the large voltage gradients at the edges of the detectors. Some groups have even been able to operate thick detectors with a single guard ring [4].

We have been developing such detectors for a range of X-ray and gamma ray applications. Started as a Con-X [5] Advanced Technology Development program, the detector program is now mostly focused on higher energy gamma ray instrumentation for ground and space-based Compton telescopes, for medical imaging [6], and for solar gamma ray spectroscopy [7]. Nevertheless, these detectors are very similar to the detectors that could be used on a next generation X-ray timing mission and they form a good basis for the design of large area detectors for such a mission. The main alternative design would be silicon drift detectors [8] that have the advantageous characteristic of being extremely low capacitance devices. They have the disadvantage of not being as mature a technology in terms of size and commercial availability.

DETECTORS

In order to make thick detectors, high resistivity material is required. The detectors were designed for 20,000 to 40,000 $\Omega\cdot$cm material currently available from Topsil [9]. With this resistivity, two-millimeter-thick detectors were expected to deplete around 800 Volts. This high voltage requires a special design near the edges of the detector where high voltage gradients will occur. A multiguard ring approach was used to provide a set of equipotentials to control the electric fields. Fig. 1 shows the inner guard rings near the corner of a detector. A total of 23 concentric guard rings were used over a width of 3 mm. As can be seen in Fig. 1, the guard ring separation increases away from the active area of the detector toward the edge. The guard rings are not kept at a specific voltage but are allowed to drift to an equilibrium.

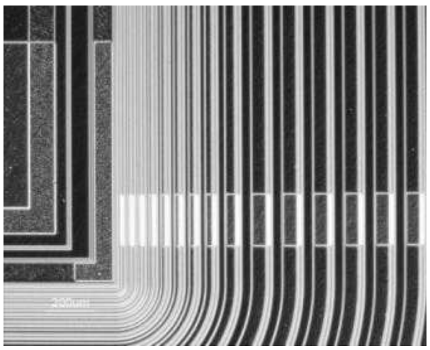

FIGURE 1. Photograph of a corner of the detector shown in Fig. 2. The central 15 guard rings are visible on the right hand side of the photograph. There are a total of 23 guard rings.

The detectors are DC coupled detectors, which means there are no de-coupling capacitors, or biasing resistors built into the detector. This choice was made because the vast majority of double-sided silicon strip detector failures occurs in this AC coupling circuitry. Since our detector pitch is relatively coarse, it is relatively straight forward to locate surface-mount capacitors and resistors near the edges of the detector. Fig. 2 shows a large 2 mm thick double-sided silicon strip detector and the associated de-coupling capacitors and biasing resistors. This detector was manufactured for us from a 10 cm-diameter wafer by SINTEF [10].

The 10-cm diameter wafer design contained a large central square double-sided detector, as well as smaller rectangular double-sided detectors, single sided detectors and test structures. The smaller double-sided detectors had the same pitch and guard ring structure as the large detector, thereby allowing us to study the effect of changing the strip length while keeping all other parameters constant. Two different types of small double-sided detectors were manufactured with different gaps between the strips. This allowed us to study the effect of strip width. The large strip detectors had an active area of 57 mm x 57 mm and 64 strips per side. This implies a strip pitch of 0.891 mm. The detectors deplete at around 700 Volts, and have a typical leakage current of 900 nA at 25°C.

To demonstrate the imaging capability of this detector, we illuminated it with the 59.5 keV photons from an ^{241}Am source. We placed a set of brass gears between the source and the detector. The image that was generated

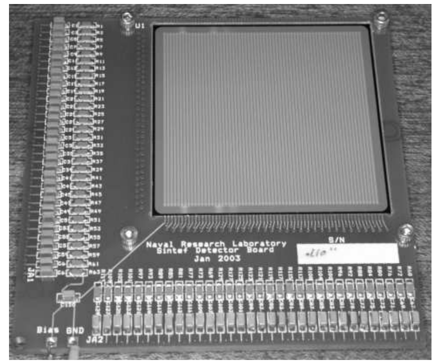

FIGURE 2. Photograph of a 2 mm thick double-sided silicon strip detector. The detector is DC coupled, and surface-mount decoupling capacitors and biasing resistors are visible on the printed circuit board holding the detector.

is shown in Fig. 3. The shadow of the gears is clearly visible. This image was generated by collecting signals from each strip of both sides of the detector. The signals were collected using hybrid preamplifiers (eV Products [11]), NIM 16-channel shaping amplifiers (CAEN [12]), and VME 32-channel peak-sensing ADCs (CAEN [12]). Each side of the detector provides one coordinate of position information, and by combining the coordinates on event-by-event basis, an effective 64 by 64 pixel detector is generated.

While a semi-conductor-based X-ray timing mission with a very narrow field of view does not require imaging, it will probably end up highly segmented for other reasons. A strip- or pixel- detector will be segmented to limit the capacitance of each strip or pixel. The alternative, the silicon drift detector, with very low capacitance, will still be limited in size due to voltage and collection time constraints. The segmentation can be useful in different ways. The partial shadow of the collimator over a set of pixels could be used to solve cases of source confusion and to collect source and background spectra simultaneously.

More interestingly, the segmentation can be used for polarimetry measurements at energies above $\sim$30 keV. Above this energy, the dominant interaction process for photons is Compton scattering. The Compton scattering cross section depends on polarization. By collecting events that interacted twice in a layer and comparing the angular dependence of second scatters around the first scatter position, a net polarization can be detected. This polarimetry feature is implicit in the design of any finely segmented detector array.

Typically, large area silicon detectors are used for particle physics and are not used to generate high resolution spectra. PIN diodes, on the other hand, have been commonly used to generate high quality X-ray spectra. There is, however, no intrinsic difference between these

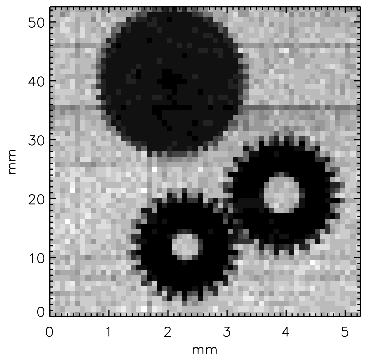

FIGURE 3. Shadowgram of 3 brass gears generated with 59.5 keV photons from an ^{241}Am source illuminating the detector shown in Fig. 2. Discrete readout electronics were used to generate the image.

two types of devices. The large strip detector shown in Fig. 2 generated spectra with an energy resolution of ∼4 keV at a temperature of 25°C. This is dominated by the contribution from the leakage current. By cooling the detector, the leakage current can be significantly reduced so that it is no longer the leading term in determining the energy resolution.

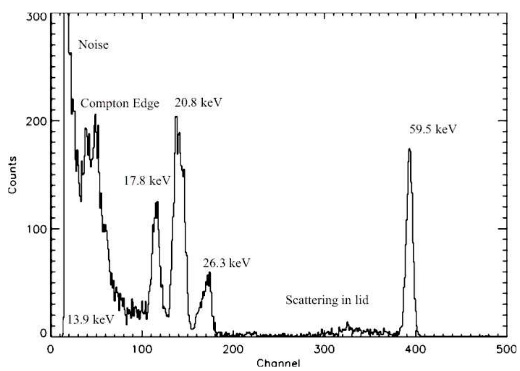

FIGURE 4. Energy spectrum of an ^{241}Am source obtained with a 2 mm thick silicon pixel detector. The energy resolution is ∼950 eV FWHM. The pixel had an active area of 4 mm x 4 mm. The spectrum was collected with discrete readout electronics. The detector was cooled to -60°C.

To demonstrate this, we cooled a 2-mm thick pixel detector with an area of 4 mm x 4 mm and a guard structure identical to the other detector. The energy spectrum obtained with an ^{241}Am source is shown in Fig. 4. The spectrum shows an energy resolution of 950 eV and was obtained at a temperature of -60°C. Similar spectra can be obtained with temperatures as high as -30°C. The spectrum shows the prominent 59.5 keV line, where the 2 mm detector still has an efficiency close to 10%. Also visible are the 17.8 keV line, the 20.8 keV line and the 26.3 keV line. The relative heights of these lines is affected by the detector efficiency and the fact that there was a 1.5 mm thick aluminum lid between the source and the detector. The lid absorbed low energy photons and Compton scattered some 59.5 keV photons causing the continuum seen in the 45-60 keV region. Also visible is the Compton edge from the 59.5 keV photons. Here are photons that Compton scattered in the pixel and then exited the detector. These are the type of events, when undergoing multiple interactions in a many pixel- or strip- detector, that will yield polarimetry information. Note that the electronic noise can be seen coming in at ∼4 keV, with a relatively large 4 mm x 4 mm pixel.

We have recently designed our next generation of large area 2 mm-thick detectors. They are based on 150 mm diameter wafers. There is a large central detector with an area of 96 mm x 96 mm, and an active area of 90 mm x 90 mm. The detector has 64 strips on each side, yielding a strip pitch of ∼1.4 mm. The corners of the detector have been rounded with a bending radius equal to the strip pitch to maximize the size of detector obtainable from a round wafer. In addition to the central detector, there are eight small detectors. They are again meant to explore some geometrical phase-space while keeping the pitch and guard ring structures constant.

There will be four different types of small detectors: detectors with wide strips, narrow strips, double-sided pixels, and pixel/strip hybrids. The pixel and strip combination might be useful for instrument designs where the pixel signal is used for spectroscopy and the strip signal is used for triggering. In many pixel detectors, the entire face is used as a source of trigger signals. In an application where a very low threshold is desired, this approach will probably not work and segmentation on both sides will probably be necessary.

ELECTRONICS

As part of our detector development effort, we are also developing a front-end ASIC (Application Specific Integrated Circuit). The ASIC is mandatory for applications that have a large number of strips or pixels. In collaboration with the University of Michigan [13], we chose the long line of VA-TA chips from IDE AS [14] as the basis for our design. The custom ASIC is in fact a combination of 2 individual custom ASICs: the VAS3 and the TAT3. They were designed and manufactured for us by IDE AS. The chips handle 32 channels and the outputs are multiplexed to external ADCs. The VAS3 provide the preamplifier and the shaping amplifier, the TAT3 provides the trigger logic and timing information.

The VAS3 chip actually has 34 channels: one additional channel is used for common-mode noise rejection; and one channel is available as a trigger channel for a pixellated detector with one large electrode on one side and 32 electrodes on the other side. The VAS3 has a low power/low noise charge sensitive preamplifier, a shaper circuit with ~1 microsecond peaking time, a peak hold, a sample and hold and serial outputs. It also contains inverters so the chip can be used on either side of a double-sided detector. In addition, it provides preamplifier outputs for the TA chip. The power consumption of the VAS3 ASIC is ~84 mW. The noise performance at the manufacturer is in the region of 300 electrons rms (or ~2.5 keV FWHM energy resolution in silicon), although we have not yet been able to reproduce this in the laboratory.

The TAT3 chip uses the preamplifed signals from the VAS3 chip and amplifies them through a fast CR-RC shaper followed by a level-sensitive discriminator. This signal is used to generate a trigger and to provide the timing measurement. Its power consumption is ~13 mW per chip.

This chip set is rather different from the usual VA-TA series in that it provides the capability of obtaining the depth of interaction of an event in the detector by measuring the difference in arrival time of a pulse on either side of the detector. This is important for thick detectors and higher energy applications such as Compton telescopes, where the three-dimensional location of an interaction is required. For X-ray timing purposes, as long as the required timing accuracy is less than a few hundred nanoseconds, this complexity is not needed. The main challenge for an X-ray timing mission will be to attain the desired low noise within the alloted power budget.

X-RAY TIMING APPLICATIONS

We have demonstrated the performance of large area 2 mm-thick silicon detectors. These detectors are very well suited for a next generation X-ray timing mission because they are rugged, they can be mass-produced, they have a good energy resolution and a smooth energy response. We will soon have detectors with an active area greater than 80 square centimeters, and hopefully also detectors with a thickness of 3 mm. The detectors are double-sided detectors due to the requirements of our high-energy gamma-ray applications.

For an X-ray timing mission where these detectors will not be stacked and imaging is not important, the detectors could probably be single-sided detectors. This will reduce the cost and complexity of the detector manufacturing and handling. The detectors will still need to be highly segmented to achieve the desired goal of operating at 2 keV. To achieve this low noise level, the detector will probably need to be segmented down to pixels of tens of square millimeters each. Alternatively, silicon drift detectors could be used. Unfortunately, silicon drift detectors are not yet available in large areas, and commercial sources for these detectors are only now emerging.

Even if silicon drift detectors were baselined for a mission, the main obstacle to achieving the goals outlined for such a mission will be the electronic noise. Assuming a 1 KW total science power budget, the power available for front end electronics will at best be 500W, or 5 mW per square centimeter. Achieving 120 e^- noise rms with 5 mW will be a challenge, even with detectors that have almost no capacitance, but it should be possible. It will require a careful interface between the design of the detector and the design of the front-end electronics.

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